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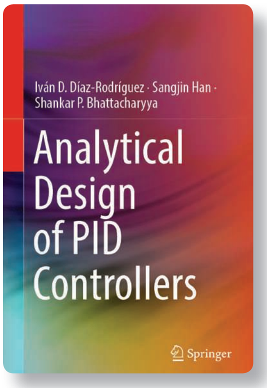

# ANALYTICAL DESIGN OF PID CONTROLLERS

by IVÁN D. DÍAZ-RODRÍGUEZ, SANGJIN HAN, and SHANKAR P. BHATTACHARYYA

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The proportional-integral-derivative (PID) controller dominates the control industry and, by some estimates, accounts for more than 95% of the controllers in use worldwide [1], [2]. Its working is based on the following simple fact: if a stable dynamic system is subject to constant reference and disturbance inputs, all signals in the system tend asymptotically to constant values and the input to each integrator tends to zero. This applies to continuous-time; discrete-time; linear; nonlinear; single-input, single-output (SISO); and multivariable, multiple-input, multiple-output systems with and without time delays. This immediately suggests that tracking and disturbance rejection of constant inputs can be accomplished by generating the tracking error and using it to drive integrators that generate the control signal. This architecture is inherently robust relative to state feedback, observer-based, high-order optimal systems [3].

This monograph is focused exclusively on the PID controller. It is timely and contributes substantially to the art and science of control system engineering.

- Timely, because PID controllers are increasingly being used in dynamically changing environments, such as those encountered in driverless cars, unmanned aerial vehicles, and distributed robotics. In these applications, there is an urgent need for design methods and algorithms that can quickly and accurately update controller gains.
- Art, because the book proposes a multiobjective approach to design, allowing the designer to creatively blend various performance measures using classical and modern approaches.
- Science, because rigorous analytical approaches to achieve such designs are also presented.

This monograph is the third in a series (the others are [4] and [5]) focused on the development of PID controller design theory based on the computation of the stabilizing set.

## CONTENTS

The book is organized into three parts. Part I lays the foundation for the rest of the book. It describes methods for the computation of the complete set of PID controllers stabilizing a given SISO linear time-invariant plant. The plant description can be in the form of a transfer function, or it may be given as frequency-response data for a continuous-time [6] or discrete-time system [7]. Clearly, every design must reside in this stabilizing set. It is shown that the stabilizing set can be computed by solving a set of linear programming problems with a scalar sweeping parameter varied over a specifiable range. The linear programming formulation results from the novel application of a root counting formula that generalizes the classical Hermite–Bieler theorem. This applies to continuous-time systems with time delay and discrete-time systems. In the latter case, the frequency response of the system is represented using Tchebyshev polynomials, which simplify the computations. An interesting by-product of these results is the computation of all stabilizing PID controllers for the Ziegler–Nichols plant (that is, first order with time delay), generalizing this classical 1942 result [8]. Another interesting result is the computation of all PID controllers that shift all the closed-loop poles to the left of a line at $s = -\sigma$, resulting in the determination of the maximum achievable $\sigma$ for the given plant [9]. This number is inversely proportional to the settling time of the step response.

Using the stabilizing set, Part II proceeds to search for achievable performance for the closed-loop system under

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PID control. For PI controllers, the design takes place over the 2D $(K_p, K_i)$ stabilizing set. The problem of achieving the classical design specifications of gain and phase margin is then discussed. It is shown that a fixed gain crossover frequency is achieved on an ellipse and that a prescribed phase margin is achieved on a straight line through the origin. The intersection of the ellipse and straight line is an *achievable* design point under PI control if and only if it lies in the stabilizing set. Such a point corresponds to a design with a given gain crossover frequency, phase margin, and gain margin specification. By reversing these steps, one can produce a controller that delivers prescribed crossover frequency, phase margin, and gain margin. The entire stabilizing set can then be mapped to the achievable gain and phase margin space indexed by crossover frequencies. This leads to design curves where the gain and phase margins can be traded against each other for each possible gain crossover frequency. Similar results are given for PID controllers, where one can exploit the 2D results by fixing one gain and sweeping over its admissible range. In this case, one obtains the achievable gain–phase margin curves indexed by gain crossover frequency for various settings of the derivative gain.

The final chapter addresses a new approach to multivariable control using the Smith–McMillan diagonal form of the plant. This allows for the design to be decomposed into a number of SISO control-loop designs to which the previous techniques can be applied. The resulting diagonal controller can then be mapped back into a controller for the original system. It is shown that stability, tracking, and disturbance rejection are preserved and that the stability margins obtained for the resulting multivariable system are the minimum of the gain and phase margins obtained for the Smith–McMillan loops. Examples illustrating this approach are also given.

In Part III of the book, $H_\infty$ optimization-based design of PID controllers for both continuous and discrete-time systems is considered. Once again, having the stabilizing set is the key to extracting the complete set of controllers achieving a prescribed level of the $H_\infty$ norm on the error.

## SUMMARY

The book presents several novel and effective approaches for the synthesis and design of PID controllers. It addresses and solves classical gain and phase margin-based designs, modern $H_\infty$ norm-based designs, and new approaches to multivariable control based on SISO methods. Both continuous-time and discrete-time systems are treated by the same methods. The methodology developed is based on research conducted at Texas A&M University over the last 20 years. It is expected that these approaches will find applications to control system design in both traditional areas as well as in new areas such as driverless cars and autonomous robots. Overall, the techniques covered in this book form a substantial contribution to the field of control, and this book is recommended for students and practitioners of control theory. As a final note, this book is dedicated to the late Prof. J.B. Pearson, who, from the outset, insisted that the robust design of servomechanisms via output feedback is the canonical problem of control theory.

> **Overall, the techniques covered in this book form a substantial contribution to the field of control, and this book is recommended for students and practitioners of control theory.**

## REVIEWER INFORMATION

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## REFERENCES

[1] A. Alqudah and A. Qasaimeh, “Design techniques study of PID controllers,” *Int. J. Comput. Digit. Syst.*, vol. 4, no. 2, pp. 101–109, Apr. 2015. doi: 10.12785/ijcds/040204.

[2] L. Desborough and R. Miller, “Increasing customer value of industrial control performance monitoring: Honeywell’s experience,” in *Proc. 6th Int. Conf. Chem. Process Control*, 2001, pp. 172–192.

[3] L. H. Keel and S. P. Bhattacharyya, “Robust, fragile, or optimal?” *IEEE Trans. Autom. Control*, vol. 42, no. 8, pp. 1098–1105, 1997. doi: 10.1109/9.618239.

[4] A. Datta, M. T. Ho, and S. P. Bhattacharyya, *Structure and Synthesis of PID Controllers*. Berlin: Springer-Verlag, 2000.

[5] G. J. Silva, A. Datta, and S. P. Bhattacharyya, *PID Controllers for Time-Delay Systems*. Basel: Birkhüser, 2005.

[6] L. H. Keel and S. P. Bhattacharyya, “Controller synthesis free of analytical models: Three term controllers,” *IEEE Trans. Autom. Control*, vol. 53, no. 6, pp. 1353–1369, 2008. doi: 10.1109/TAC.2008.925810.

[7] L. H. Keel, S. Mitra, and S. P. Bhattacharyya, “Data driven synthesis of three term digital controllers,” *SICE J. Control, Meas. Syst. Integr.*, vol. 1, no. 2, pp. 102–110, 2008. doi: 10.9746/jcmsi.1.102.

[8] J. G. Ziegler and N. B. Nichols, “Optimum settings for automatic controllers,” *Trans. ASME*, vol. 64, pp. 759–768, 1942.

[9] S. Han and S. P. Bhattacharyya, “PID controller synthesis using a $\sigma$-Hurwitz stability criterion,” *IEEE Control Syst. Lett.*, vol. 2, no. 3, pp. 525–530, 2018. doi: 10.1109/LCSYS.2018.2842784.